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Abstract

The paper reviews a recent study to identify practical, highly durable, alternate thermal protection systems for the Shuttle Orbiter and presents a status report on alternate TPS technology developments. The study identified candidate concepts, assessed the impact on the Shuttle Orbiter performance, life cycle cost, and risk, and defined technology advances required to bring the selected TPS to operational readiness. Within the study guidelines the "best" system is a blend of mechanically attached metallic and carbon-carbon TPS concepts. These alternate concepts offer significant improvements in durability and are mass competitive with the current ceramic tile reusable surface insulation. Programmatic analysis indicates that, with adequate resources, approximately five years are required to bring the concepts to operational readiness.

Introduction

Prompted by damage to the thermal protection system (TPS) of the Space Shuttle Orbiter during the first ferry flight,[1] the NASA Office of Space Transportation Systems (OSTS) intensified analytical and experimental investigations[2-6] to understand and improve the static and dynamic behavior of the ceramic Reusable Surface Insulation (RSI) tiles and the felt Strain Isolation Pad (SIP) used to accommodate differential thermal and mechanical deformations between the tiles and the structure. As part of this effort, a tile densification process was developed[2,4] that increases the strength of the tile system.

OSTS also initiated and funded an assessment[7,8] of alternate, more durable, TPS to determine their applicability to the Shuttle and the state of technology readiness of these systems. The NASA Langley Research Center was asked to manage the study since virtually all research on alternate TPS concepts for future space transportation systems was being conducted at Langley under the auspices of the NASA Office of Aeronautics and Space Technology. The specific objectives of the study were to:

- Define the "best" alternate thermal protection system for application to the Space Shuttle Orbiter considering only metallic, ablator, and reinforced carbon-carbon concepts.
- Define the technology requirements to bring the selected TPS up to operational readiness.
- Prepare plans, schedules and cost estimates for the required research, development, design, qualification, fabrication, installation and maintenance of the selected TPS.

After 3 flights, the performance of RSI is encouraging in that no densified tiles have been lost during flight.[9-11] However, the RSI is nevertheless a very fragile system. The fragility, coupled with the nonlinear characteristics of the SIP[2] and the resulting uncertainty in the "life" of any given tile, leads to continued interest in alternate TPS concepts that offer increases in durability and life without significant mass penalties.

This paper reviews the technical aspects of the alternate TPS study and provides a status report on alternate TPS technology developments.

Alternate TPS Study

Guidelines

To limit the scope (and cost) the study was constrained by closely defined guidelines. Specifically, the study considered only areas currently covered by low temperature and high temperature reusable surface insulation (LRSI and HRSI) ceramic tiles. Areas not considered were the wing leading edges and the nose cap where carbon-carbon hot structure is used and low temperature areas, such as the upper surface of the fuselage, where flexible reusable surface insulation (FRSI), a silicon rubber impregnate nomex felt, is used. The study was also limited to metallic, carbon-carbon, and ablator TPS concepts or, combinations thereof, and was not to consider advanced ceramic insulations[12] such as fiberous

reinforced composite insulation (FRCI), advanced flexible reusable surface insulation (AFRSI), and taylored advanced blanket insulation (TABI). (FRCI, AFRSI, and TABI were excluded since their status and potential were known to Shuttle project management.) Ablators were restricted to areas that exceeded the maximum use temperature range of metallic concepts. The study considered all aspects of Shuttle operations including lift-off and ascent, orbit, entry, landing, and ground operations. The study was directed toward acreage applications but examined the effects of singularities in sufficient depth to assess their impact on the feasibility of the basic concepts. These singularities included thermal barriers around fixed and moving parts, (i.e., external tank umbilical doors, landing gear doors, crew cabin side hatch, etc.), interfaces with fixed penetrations (i.e., windows, ducts, drains, etc.) and interfaces with adjoining TPS concepts.

Team

An industrial team headed by Rockwell International, fig. 1, was selected for the study. The team approach provided a broad and diversified background and helped to ensure an objective consideration of the latest advances in technology. The study was under the auspices of a NASA advisory group led by the Langley Research Center with members from various disciplines (materials, structures, aerothermodynamics, acoustics, etc.) with active participation from NASA Centers responsible for Shuttle integration and operations, Johnson and Kennedy Space Centers, respectively.

Plan

The initial phase of the assessment defined representative study areas on the Shuttle and associated environments and identified candidate TPS design concepts. Integrated TPS concept/orbiter point designs were then generated and optimized on the basis of Shuttle design environments and criteria. A merit function evaluation methodology based on mission impact, life cycle cost, and risk was developed to compare the candidate concepts. Through successive screening the field of concepts for the study areas was narrowed. Complete systems for the Shuttle were synthesized, their impact on the Shuttle mission was assessed, and a "best" alternate TPS system was selected. Voids and deficiencies in TPS technology were identified, along with recommended activities to overcome them. Finally, programmatic plans, including rough order of magnitude costs and schedules, were developed for all activities required to bring the selected alternate system to operational readiness. Whenever possible in the winnowing process, quantitative analyses were used. These analyses included both sophisticated computer and manual analyses of thermal and structural performance and frequently involved trade studies to size components of the concepts. However, as is always the case in studies of this type, many of the decisions were based perforced on qualitative analysis, concensus judgment, and even pragmatic considerations.

Study Areas

Initially, ten study areas and a multitude of TPS concepts were considered. However, to permit a more in-depth assessment, the field was narrowed to four areas and fifteen concepts for most of the study. The four areas, fig. 2, were selected primarily on the basis of thermal environment which is the premier discriminator; however, in the selection of the point design locations also shown in fig. 2, additional factors such as singularities and the type of underlying structure were considered.

Design conditions for each design location are presented in Table 1 and fig. 3. Table 1 indicates that besides high surface temperature during entry, the TPS is exposed to relatively severe acoustic conditions, moderate shock pressure loads, and moderately high temperatures during ascent. The entry thermal environment, as characterized by surface temperature histories presented in fig. 3, and the local lumped thermal mass of the structure (not presented) were used to size the thermal insulation. Interestingly, in addition to magnitude, the time of maximum heating varies for the different areas. This is due to the onset of turbulent heating for the two aft lower surface areas (Areas II and III). The design conditions presented in Table 1 and fig. 3 are for Shuttle Orbiter trajectory 14414.1C and are, strictly speaking, for the vehicle with an RSI external surface. Effects of interactions of the alternate TPS on the design environment, although considered qualitatively, were not factored into the study quantitatively.

Generic TPS Concepts

The TPS concepts, although of different material and construction, can be divided into two generic types--prepackaged and standoff--as indicated by fig. 4. The figure provides a brief pictorical introduction to the concepts and nomenclature of the concept screening process. The prepackaged concepts, as the name implies, consist of discrete units or tiles each comprised of a radiative heat shield outer surface with encapsulated insulation (if required) and are attached as a single assembly with clips or slip attachments which permit differential thermal growth between the TPS and the primary structure. Each standoff concept consists of a radiative heat shield, a separate insulation package, and flexible supports (or standoffs) which attach the heat shield to the primary structure and accommodate differential thermal growth. The concepts are further identified by material and type of structure employed in the construction of the outer radiative heat shield surface as shown by the section sketches in the figure. The structural designators with the exception of multiwall are in common usage. Multiwall is a unique concept consisting of alternate layers of flat and dimpled sheets of foil material joined to form an insulating structural sandwich. Ablators, which would have introduced a third generic type, were eliminated early in the study when it was determined that refractory alloys and carbon-carbon TPS could accommodate the highest use temperature postulated for the Shuttle.

Concept Screening

The essence of the study is briefly summarized in Table 2. Although portrayed as a simple two step operation, the actual screening was a highly interactive, iterative process. In general,

choices in the initial screening were based on technical considerations; whereas, choices in the final screening were based on more of an election of alternatives reflecting pragmatic considerations. For more details of the screening process, the reader is referred to references 7 and 8.

For the lowest temperature area (Area I) only the prepackaged titanium multiwall was considered since relatively low heat fluxes in this area permit insulation that is too thin for flexible standoffs to function properly. Additionally, the temperatures are well within the capabilities of titanium which is significantly lighter (by almost a factor of two) than the more dense superalloys. This, of course, provides an incentive for extending the temperature range for the titanium concept beyond the relatively conservative upper limit of 1000°F used in this study. Finally, the multiwall concept, which will be discussed more fully subsequently, represents a relatively mature technology (from a research and technology point of view).

For the intermediate temperature ranges (Areas II and III) a variety of superalloy configurations and a single carbon-carbon concept were considered. During the initial screening of the prepackaged concepts, the multiwall configuration, although shown to be slightly lighter because of somewhat arbitrary minimum gage constraints, was eliminated because the honeycomb construction provided a larger structural margin, a more readily analyzed configuration, and potentially, a more durable TPS. In contrast to the lower temperature all metal titanium multiwall TPS, the higher temperature superalloy prepackaged configurations employ encapsulated fibrous insulations. Thus the structural and thermal functions are separated, and multiwall construction which compromises structural performance to improve thermal efficiency is not required.

Although corrugated surface, metallic standoff configurations represented the most highly developed concepts,[13,14] they were also eliminated in the early screening because of concern about the effects of the corrugations on local heating and the potential effects of surface roughness on flow transition.[15] In addition, these configurations had more separate parts and required extensive in situ installation, which made fabrication, installation, removal, and inspection more difficult and potentially more costly than for other configurations.

The prepackaged superalloy honeycomb concept and the superalloy waffle, superalloy honeycomb, and carbon-carbon rib stiffened standoff concepts were retained through the initial screening. The metallic standoff concepts were eliminated in the final screening primarily because of a lack of on-going supportive research. The carbon-carbon configuration, although significantly heavier than the superalloy concept, was retained for the higher temperature regions of Area III because of uncertainties in the heating environment and limited overtemperature capabilities of superalloys.

Carbon-carbon standoff TPS was also selected for the highest temperature area (Area IV). Initially, because of their more advanced stage of development, refractory alloys were thought to be the leading contenders for this area despite known mass penalties and oxidation protective coating limitations. However, during the course of the study, team members became convinced that recent technology advances[16] made the much lower mass carbon-carbon configuration a more viable concept. As shown in fig. 5, advanced carbon-carbon (ACC) has approximately one-half the oxidation mass loss and more than twice the strength of the reinforced carbon-carbon (RCC) currently employed on the Shuttle Orbiter. These improvements permit the use of thinner gage, lower mass panels needed for the lightly loaded TPS heat shields. The prepackaged carbon-carbon concept was rejected because of the thermal incompatibility between carbon-carbon and metallic components, and the mass of the specific configuration studied. Although these problems might be overcome through ingenious design, the low thermal expansion and limited strength of carbon-carbon (even ACC) make it more amenable to the standoff design.

TPS Mass

The realism of the unit masses developed in the study is illustrated by fig. 6. Unit masses of the lightest concepts for the four point designs of the study are compared with: 1) the mass of the reusable surface insulation (RSI) currently on the Shuttle Orbiter (shown by the hatched band) and 2) the unit masses of fabricated and tested concepts (shown by the darkened symbols). The latter indicate improvements which have been achieved through metallic TPS research from 1972 through 1981,[17,18] that make the metallic TPS concepts mass competitive with the RSI. The study masses are shown to be comparable to the most recent metallic TPS concepts, which tends to lend credence to the masses generated in the design study. As will be shown subsequently, mass is the strongest discriminator in TPS selection.

Alternate TPS Concept Application

Potential operational impacts to the orbiter were assessed throughout the analysis and design efforts. The factors considered included total TPS mass, payload capability, changes in outer moldline, turnaround time, and flight trajectory. As part of the concept screening process, a number of complete TPS systems were synthesized to assess the impact of the individual concepts on the total orbiter system performance, operational schedule, and cost. The lightest system consisted of titanium multiwall in Area I, superalloy honeycomb prepackaged in Areas II and III, and advanced carbon carbon standoff in Area IV. Thus in effect, a three concept system evolved.

The lightest system was not selected as the "best" system because of concerns about the impact of the alternate concepts on orbiter surface roughness. During entry, thermal gradients in the metallic TPS panels will produce panel bowing ranging up to 0.25 in. amplitude. The effect of this panel bowing is a major concern since it may induce boundary layer transition from laminar to turbulent flow. Premature boundary layer transition impacts not only the maximum surface temperature by increasing heating rates but also the overall TPS mass (thickness) due to increased total heat load. Fortunately, the time of maximum bowing does not coincide with the time when

boundary layer transition is most critical. However, the type of roughness generated by the bowing is significantly different from the step and gap roughness encountered with the Shuttle RSI and the impact on flow transition is unknown. Assessment of the overall effects of panel bowing on the aerodynamic heating environment was beyond the scope of the study, since adequate determination of such effects requires extensive testing.

Heating calculations indicate that, on the bottom surface of the Shuttle Orbiter, early transition can induce surface temperature in excess of 2000°F over large areas that normally experience maximum temperature of 1800°F.[8] Because of concern for the potential overtemperature problem, the "best" system, shown in fig. 7, was selected. The "best" system is a perturbation of the lightest system that limits the superalloy honeycomb concept to 1800°F and uses ACC above 1800°F. The increased use of carbon-carbon provides a significant gain in overtemperature capability but exacts a sizable mass penalty. Increasing the surface area covered by ACC from 1,183 ft^2 to 2,503 ft^3 increases the estimated total system mass by 1,238 lb or approximately an 8-percent increase in TPS mass.

Details of the selected TPS concepts are presented in figs. 8 and 9. A common feature of all the concepts is the overlap between panels. These overlaps eliminate open gaps and are oriented to provide rearward facing steps thereby reducing hot gas inflow and direct heating, and minimizing surface roughness effects that may trigger flow transition.

Titanium multiwall appears suitable for approximately 3243 ft^2 of the Shuttle surface (fig. 7). The basic titanium multiwall concept, fig. 8, is a one foot square, clip attached tile fabricated of 6Al-2Sn-4Zr-2Mo titanium. The 1000°F design (fig. 6) is approximately 0.7 inch thick and consists of four dimpled 0.003 inch sheets with three flat 0.0015 inch interposed septum sheets sandwiched between a 0.003 inch inner face sheet and a 0.004 inch outer face sheet. The entire assembly, including 0.003 inch thick corrugated sidewalls, is Liquid Interface Diffusion (LID)* bonded. The resulting all metal sandwich serves as both a structure and an insulator. Additional details of the evolution of multiwall and the companion prepackaged superalloy honeycomb concept are presented in reference 18 and 19.

Prepackaged superalloy honeycomb tiles appear suitable for approximately 2,160 ft^2 of the Shuttle surface, fig. 7. The basic tile, fig. 8, is similar in size, external appearance, and attachment method to the titanium multiwall tile; however, the interior construction differs markedly. The 1900°F design (fig. 6) weighs approximately 2.1 pounds including attachment clips. The outer panel is a 0.28 inch thick Inconel 617 honeycomb sandwich with 0.005 inch thick face sheets, the inner panel is a 0.17 inch thick 6AL-4V titanium honeycomb sandwich with 0.006 inch thick face sheets, and the corrugated side closures are of 0.003 inch thick Inconel 617. All honeycomb cores have 3/16 inch square cells and are of 0.0015 foil. The fibrous insulation consists of 0.50 inch of 6.0 lb/ft^3 Cerachrome, and 1.30 inches of 3.5 lb/ft^3 Q-Fiber Felt. The tiles are assembled in a three step braze-bond process.

The ACC standoff TPS selected for the highest temperature areas, fig. 7, evolved concurrently with the alternate TPS study and is the only one of the three concepts that has not been fabricated. As conceived, the basic ACC heat shield, fig. 9, would be 3 feet square. The use of a larger unit than that for the metal concepts appears feasible because of the relatively low coefficient of thermal expansion of carbon-carbon. The ACC heat shield is of 6 ply carbon cloth composite construction with 13 to 18 ply orthogonal stiffening ribs. (During fabrication the organic matrix is carbonized; therefore, the term carbon-carbon.) The shield is supported by 17 standoff attachment posts, therefore the concept is often designated by the term "ACC multipost." The posts are oxide dispersion strengthened alloy or coated columbium and range from approximately 1.8 to 3.2 inches long depending upon the required insulation thickness. All of the post have provisions for minor height adjustments. Fourteen posts are mounted with spherical attachments which permit unrestrained thermal expansion of the heat shield, and three are attached with single axis pivots oriented to permit thermal expansion but restrain rigid body movement of the shield. As originally conceived, and as used in the alternate TPS study, most of the fibrous insulation was encapsulated in foil to exclude water intrusion; however, for the higher temperature applications the outer layers of the insulation exceed the maximum use temperatures of foils. These layers were not encapsulated but relied on an ACC edge skirt and the overlapping edges to exclude water. (Currently it is envisioned that all of the insulation will be encapsulated in a finely woven alumina borosilicate cloth.) The exact mix of insulation types depends upon the service temperature. In order of descending temperature capabilities, the leading candidates are 3.5 lb/ft^3 Saffil Alumina, 3.5 lb/ft^3 Q-Fiber Felt, and 1.1 lb/ft^3 Astroquartz.

Sensitivity Studies

Sensitivity studies determined the influence of various factors on the total TPS system lifetime costs. These studies indicated that TPS mass was, by far, the most important parameter. As indicated in fig. 10, a 10 percent change in mass produces a 118 percent change in total lifetime costs whereas comparable changes in material cost, and operational and support cost produce only 12 and 2.8 percent changes in total lifetime cost, respectively. The lack of sensitivity to material costs is understandable since they are essentially nonrecurring, however operational and support costs, like mass, are recurring cost factors. The lack of sensitivity to operational and support costs stems from the refurbishment rates postulated for the selected TPS concepts. These refurbishment rates, which pessimistically involve replacement of approximately 30 TPS panels per flight, were derived from failure modes and effects analyses. The required inspection and refurbishment can be completed within about 40 hours of the 117 hours available for TPS maintenance. If the maintenance requirements were drastically increased, or the time for other turn around operations were greatly decreased, so that TPS maintenance became

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the critical path, the sensitivity to operation and support cost would increase dramatically.

Costs

The effects of TPS system selection on the total TPS lifetime cost are illustrated in fig. 11. The costs shown in the figure were normalized based on the initial investment and installation cost of retrofitting three Shuttle orbiters with the lightest alternate TPS system. The total economic costs are dependent upon the number of flights, the direct operational and support costs per flight, and the delta payload mass cost per flight. The latter costs are based on the estimated cost per pound of payload to orbit for a fully loaded Shuttle and the payload mass delta engendered by the change in TPS mass relative to the present RSI system. (Even the most conservative of the TPS systems shown in fig. 11 was slightly lighter than the baseline RSI system.) The figure was developed for this paper using the methodology of reference 7 and is based on finalized alternate TPS system masses which include an arbitrary 20-percent design mass growth contingency plus mass estimates for TPS interfaces, penetrations, and closeouts. It is also based on baseline orbiter RSI TPS mass of 16,139 pounds, a 65,000 pound payload for every launch, and a cost of $615 per pound of payload to orbit (i.e., $40 million per flight). Similar figures for other assumptions are presented in reference 8.

Fig. 11 shows that the choice of the more conservative "best" system instead of the lightest, although not producing a significant change in the initial investment cost, results in approximately a 25 percent increase in the total TPS lifetime cost of a three vehicle, 100 flights per vehicle program. The figure also shows that the total conservatism (surface roughness and mass growth contingency) of the study results in an increase in the total lifetime cost that is approximately 160 percent of the initial acquisition cost. This increment, which represents almost $500 million, highlights the need for, and benefits of, additional research to understand the thermal environment, and optimize and verify the TPS concepts. With a higher payload to orbit cost rate and/or additional flights the total impact would be even greater.

Risks and Technology Status

The risk and technology status evaluations were the most subjective of the assessments. They represent the consensus of both the industry and NASA team. All three risks (technology, cost, and schedule) were rated low to moderate for each of the concepts in the selected system. No essential technology breakthroughs or critical major manufacturing advances were identified.

Technology status was based on the flow diagram presented at the top of Table 3. Although the distinction is somewhat arbitrary, the first six items are considered research efforts; whereas the remaining four are development tasks. In the table, a rating of zero indicates that there has been no work in that particular area, a rating of 1 indicates that some work has been done, but additional enabling research development is required to support the next phase of the effort. A rating of 2 indicates that adequate information is available to support the next phase; however additional enhancing research may be highly desirable. For example, sufficient material data is available to permit the design and fabrication of the titanium multiwall concept; however, improved knowledge of foil gage titanium properties might permit a reduction in concept mass. The gradation employed, although sufficiently fine to provide considerable discussion during the rating process, does not fully reflect the technology status of the concepts. For example, in the category of concept development tests, both titanium multiwall and the superalloy honeycomb concepts have 1 ratings, even though the former is much closer to a 2 rating than the latter. The unilateral updating of the status of the superalloy honeycomb concept by the current authors reflects the technology advances* that have occurred since the completion of the study.

It is apparent from the table that the two metallic concepts are much nearer to a state of technology readiness than the ACC concept and that none of the concepts have progressed into the development stage. The single most significant research deficiency for all of the concepts is in concept development testing which represents the culmination of the research phase and is the most costly, hence most deficient, phase of the research process. The alternate TPS assessment study concluded that it would require one to three years to complete the required research and two to four years for development before delivery of the first ship set of alternate TPS provided the effort proceeded at a cost effective pace.

Alternate TPS Research

The three alternate TPS concepts selected for the "best" system are being actively studied at the Langley Research Center. The titanium multiwall concept is by far the most mature. As illustrated by fig. 12, a first generation multiwall concept was subjected to a broad range of environmental testing and analytical studies including aerothermal testing of a nine panel array in the Langley 8-Foot High Temperature Structures Tunnel (8' HTST). Highlights of the various studies are presented in reference 18. From these analytical and environmental studies and information gleaned from the alternate TPS study, modifications were evolved and a second generation of titanium multiwall has emerged. These modifications included changing the scarfed edge closure to a vertical closure and changing from a staggered to an inline tile alignment to improve the thermal expansion compatibility, and changing the alloy selection and bond node size to enhance structural performance.

The current status of the metallic concepts is illustrated by the hardware photographs presented in fig. 13. The upper photograph shows a curved titanium multiwall tile that was built to assess the fabricability of curved tiles. (The stepped-edge closure of this tile represents an intermediate stage of development between the scarfed edges of the first generation concept and the vertical edges of the second generation concept.) This effort, which is documented in reference 20, showed conclusively that fabrication

*Contract NAS1-15646

of single curvature multiwall tiles with a radius of 12 inches is feasible.

The center photograph shows the first second-generation titanium multiwall tile fabricated.* Preliminary developmental tests by the fabricator have verified previously mentioned structural design improvements incorporated in the second generation concept. Approximately 24 of these tiles, including a large array for aerothermal testing, are being fabricated for NASA environmental tests.

The bottom photograph shows the first prepackaged superalloy honeycomb tile fabricated.* Although this represents a first generation superalloy honeycomb concept, design improvements from the multiwall research have been incorporated in the concept. Preliminary developmental tests by the fabricator have confirmed the predicted structural and thermal performance of the concept. Approximately 25 of these tiles including a large array are also being fabricated for NASA testing.

Current Langley Research Center alternate TPS concept research activities are illustrated by fig. 14. As indicated previously, large numbers of flat metallic TPS tiles are being fabricated for environmental tests similar to those for the first generation titanium multiwall concept. These tests will include aerothermal tests of the arrays depicted at the top left of the figure in the Mach 7 hypersonic environment of the 8' HTST. This facility can produce temperatures up to approximately 1900°F on the array surface. The tests will include exposure of undamaged tiles and tiles that have sustained prior lightning strike and foreign object impact damage.

Research on the superalloy concept is being extended to curved surfaces. A 16 element array of curved tiles will be fabricated for aerothermal testing in the 8' HTST on an existing curved surface test apparatus. Tests of this array, depicted at the lower right, will assess the effects of strong pressure gradiants and non-uniform heating on concept performance.

Langley has conducted environmental test and has sponsored research** on the development of improved matrix and advanced coating of carbon-carbon which has led to advanced carbon-carbon. This work spawned the ACC TPS concept. However, to date, there has been no experimental verification of the ACC TPS concept. A contract† has been initiated for the fabrication of a four element test array for tests in the Langley 20 MW Aerothermal Arc Tunnel. The array depicted at the bottom left of fig. 14 represents the juncture of four adjacent panels and will permit an assessment of aerothermal performance and hot gas ingress of the overlapping joints at surface temperatures in the range of 2300°F. Additional small specimens of thin gage material are to be fabricated for foreign object damage assessment.

*Contract NAS1-15646.
**Contract NAS1-15722
†Contract NAS1-16957

Concluding Remarks

Concern for the durability of the reusable surface insulation (RSI) currently employed on the Shuttle Orbiter prompted a study to identify practical, highly durable, alternate thermal protection systems (TPS) for the orbiter and to define the technology advances required to bring the selected TPS to operational readiness. The study considered mission impact, life cycle costs, and risks; and selected, through successive screening of TPS candidates, a single "best" alternate TPS system. The "best" system consists of mechanically attached metallic and carbon-carbon TPS concepts employing a titanium multiwall prepackaged concept at temperatures below 1000°F, a superalloy honeycomb prepackaged concept at temperatures between 1000°F and 1800°F, and an advanced carbon-carbon multipost standoff concept above 1800°F. The alternate system is mass and cost competitive with the RSI tiles currently used on the Space Shuttle Orbiter and offers the inherent durability associated with metals and carbon-carbon. The technical, cost and schedule risks associated with the alternate system were rated low to moderate. Mass was identified as the strongest single factor driving total system costs and concern about the uncertain effects of surface roughness on heating significantly impacted the mass of the selected system. The lack of experimentally verified concepts was cited as the most significant technological deficiency.

Ongoing research at the Langley Research Center is directed toward experimentally verifying the three concepts. However, with adequate resources approximately five years are required to bring the concepts to operational readiness.

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TABLE 1. DESIGN CONDITIONS AT STUDY LOCATIONS

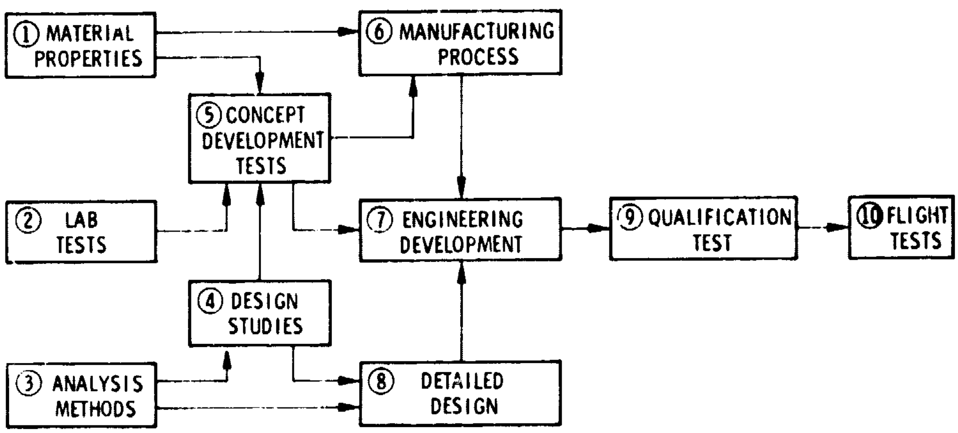
LOCATION	ASCENT					ENTRY	
	THERMAL	ACOUSTIC		SHOCK PRESSURE		THERMAL	SHOCK PRESSURE
	TEMP. °F	dB	TEMP. °F	psi	TEMP. °F	TEMP. °F	psi
I	620	161	100	.5	250	1020	.36
II	970	165	650	1.0	600	1600	.55
III	1080	160	80	.5	380	1680	.30
IV	960	158	100	.8	220	2350	.38

TABLE 2. CONCEPT SCREENING SUMMARY

AREA (TEMP)	CONCEPT TYPE	CONCEPT MATERIAL/STRUCTURE	UNIT MASS, psf	SCREENING RESULTS INITIAL	SCREENING RESULTS FINAL
I (< 1000°F)	PREPACKAGED	TITANIUM/MULTIWALL	0.75	RETAINED	SELECTED
II (1000°F TO 1600°F)	PREPACKAGED	SUPERALLOY/MULTIWALL	1.36	INFERIOR TO HONEYCOMB	—
		SUPERALLOY/HONEYCOMB	1.41	RETAINED	SELECTED
	STANDOFF	SUPERALLOY/WAFFLE	1.66	RETAINED	NO ONGOING RESEARCH
		SUPERALLOY/HONEYCOMB	1.54	RETAINED	NO ONGOING RESEARCH
		SUPERALLOY/CORRUGATED	1.79	ROUGHNESS & LOCAL HEATING	—
III (1600°F TO 2000°F)	PREPACKAGED	SUPERALLOY/HONEYCOMB	1.50	RETAINED	SELECTED
	STANDOFF	SUPERALLOY/WAFFLE	1.72	RETAINED	NO ONGOING RESEARCH
		SUPERALLOY/HONEYCOMB	1.60	RETAINED	NO ONGOING RESEARCH
		SUPERALLOY/CORRUGATED	1.84	ROUGHNESS & LOCAL HEATING	—
		CARBON CARBON/RIB STIFF.	1.84	RETAINED	SELECTED*
IV (> 2000°F)	PREPACKAGED	REFRACTORY ALLOY/WAFFLE	3.44	HEAVY-LIMITED LIFE	—
		CARBON-CARBON/RIB STIFF.	3.32	THERMAL INCOMPATIBILITY	—
	STANDOFF	REFRACTORY ALLOY/WAFFLE	3.17	HEAVY-LIMITED LIFE	—
		CARBON-CARBON/RIB STIFF.	2.31	RETAINED	SELECTED

*FOR TEMPERATURES ABOVE 1800°F

TABLE 3. ALTERNATE TPS TECHNOLOGY STATUS EVALUATION



	ITEM	PREPACKAGED TITANIUM MULTIWALL	PREPACKAGED SUPERALLOY HONEYCOMB	STANDOFF CARBON-CARBON	RESEARCH/DEVELOPMENT TIME REQUIRED
RESEARCH	1. MATERIAL PROPERTIES	2	2	1	ONE TO THREE YEARS
	2. LAB TESTS	1	1	1	
	3. ANALYSIS METHODS	1	2	2	
	4. DESIGN STUDIES	2	1(2)	2	
	5. CONCEPT DEVELOPMENT TESTS	1	0(1)	0	
	6. MANUFACTURING PROCESS	2	1(2)	1	
DEVELOPMENT	7. DETAIL DESIGN	0	0	0	TWO TO FOUR YEARS
	8. ENGINEERING DEVELOPMENT	0	0	0	
	9. QUALIFICATION TESTS	0	0	0	
	10. FLIGHT TESTS	0	0	0	
	0 - NONE AVAILABLE		1 - SOME AVAILABLE		2 - ADEQUATE AVAILABLE

( ) UNILATERALLY UPRATED BY AUTHORS; REF. CONTRACT NAS1-15646

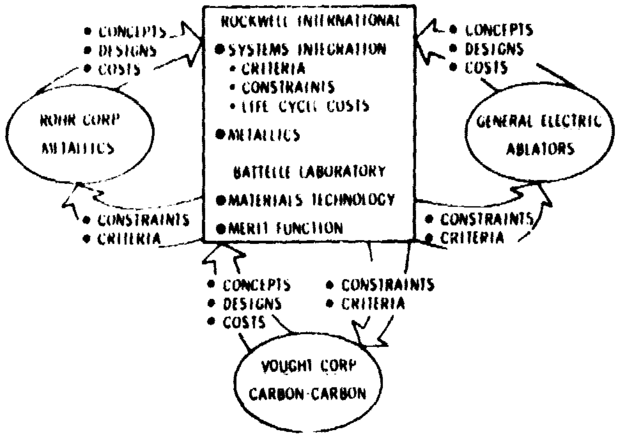


Fig. 1 Alternate TPS study team.

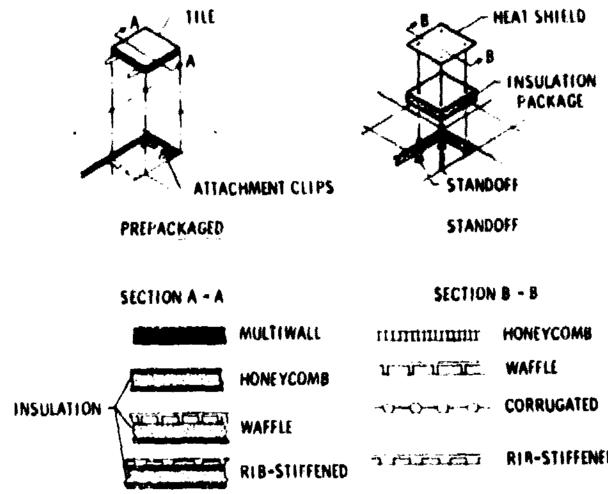


Fig. 4 Generic alternate TPS concepts.

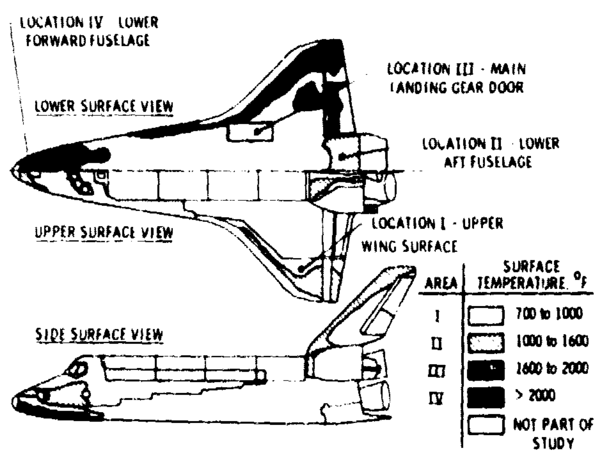


Fig. 2 Orbiter study areas.

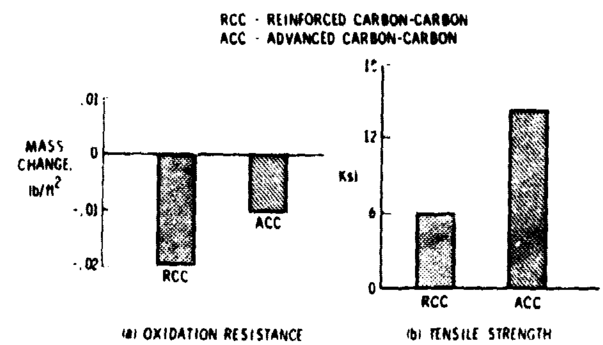


Fig. 5 Carbon-carbon properties after exposure to 100 thermal and pressure mission cycles. Maximum temperature 2450°F.

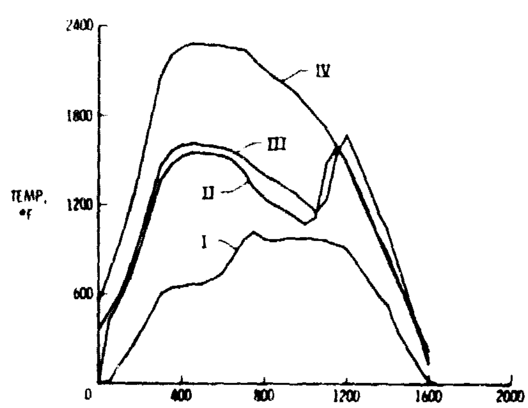


Fig. 3 Entry surface temperatures at study locations.

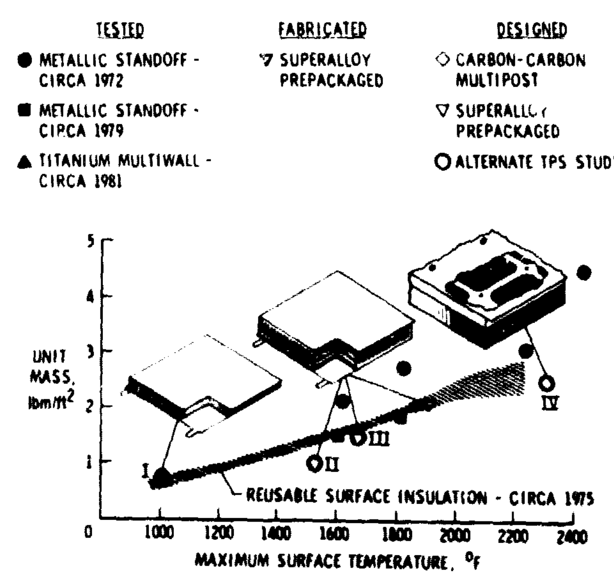


Fig. 6 Mass characteristics of TPS sized for Shuttle Orbiter application.

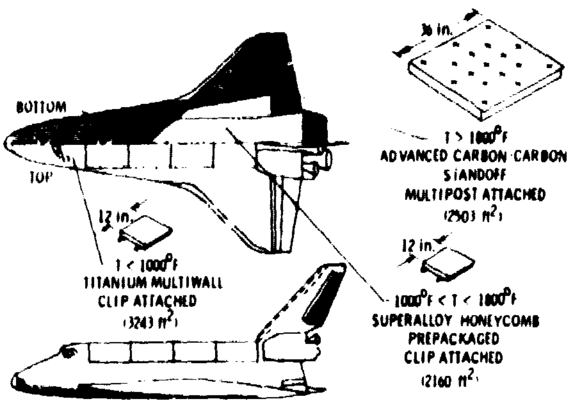


Fig. 7 Alternate TPS concept application.

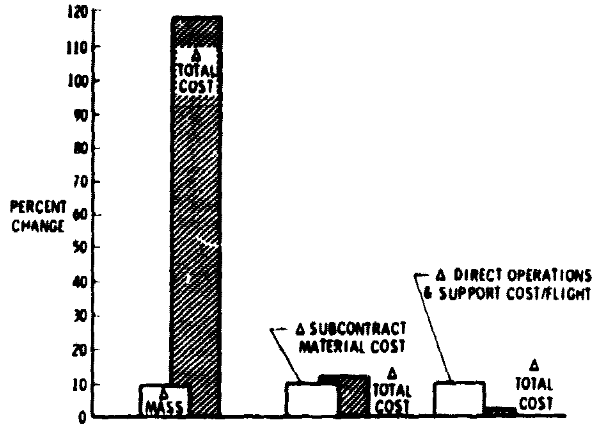


Fig. 10 Alternate TPS system sensitivities.

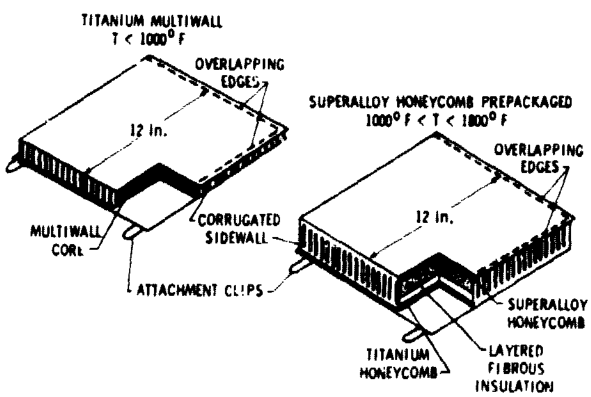


Fig. 8 Selected prepackaged metallic TPS concepts.

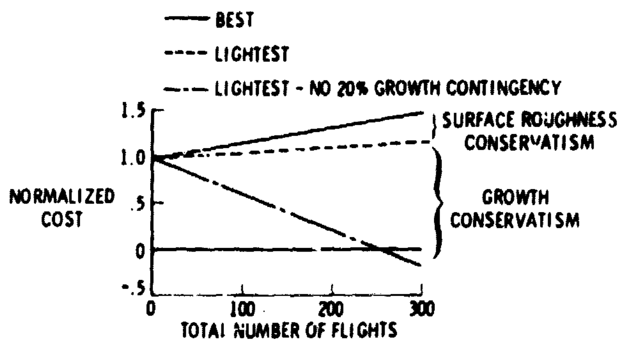


Fig. 11 Total alternate TPS system normalized costs.

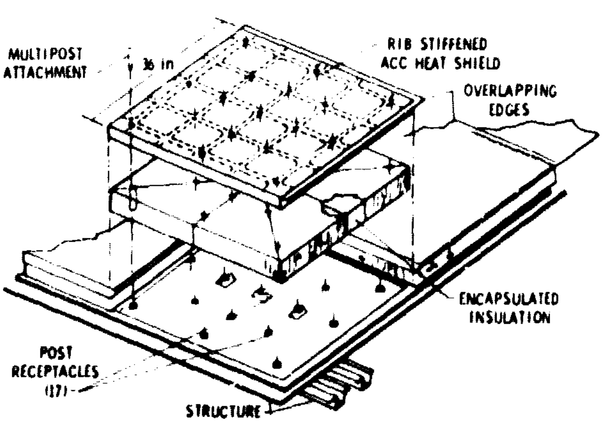


Fig. 9 Advanced carbon-carbon multipost standoff TPS concepts. T > 1800°F.

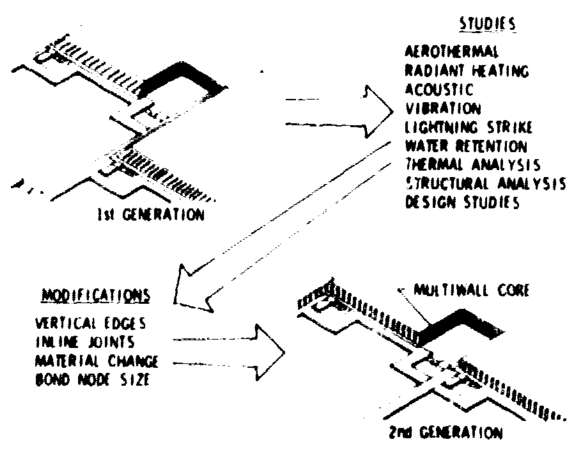
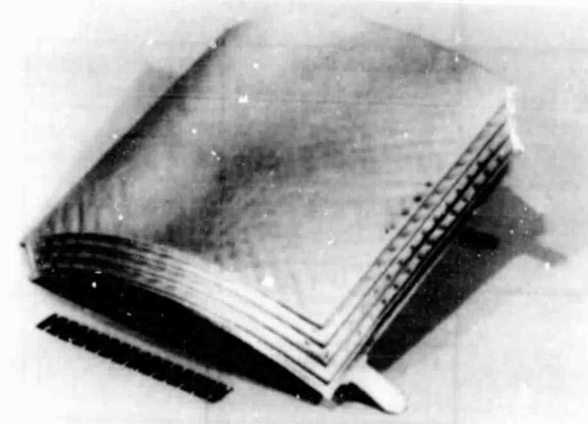
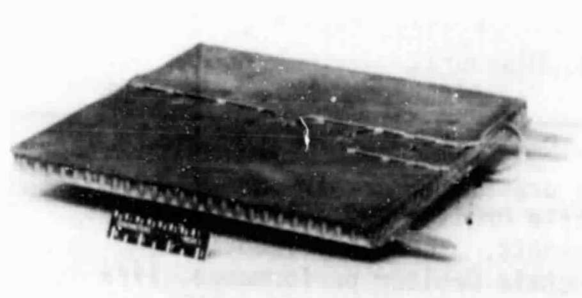


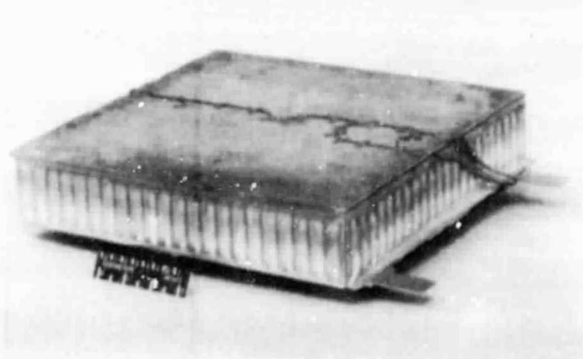
Fig. 12 Titanium multiwall concept evolution.



a) Curved titanium multiwall



b) Flat titanium multiwall



c) Flat superalloy honeycomb

Fig. 13 Prepackaged alternate TPS hardware.

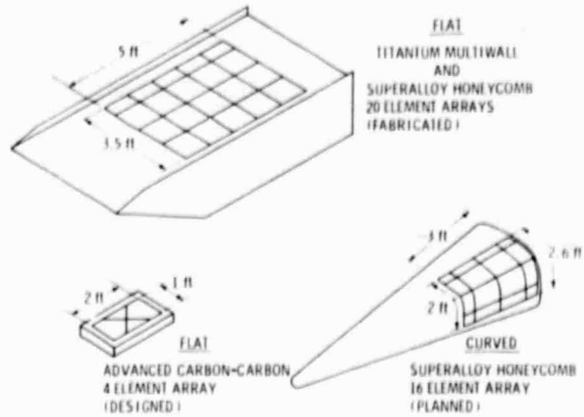


Fig. 14 Alternate TPS research activities at Langley Research Center.